Submitted to Advanced Materials

High Strain Actuator Materials Based on Dielectric Elastomers*

By Ron Pelrine, Roy Kornbluh, Guggi Kofod†

Actuator materials convert input energy to mechanical output energy. Electromagnetic actuation, whether in motors, voice coils, or solenoids, has dominated electrical actuator technology for most of the last century. Other commercial actuator technologies such as piezoelectrics have (although important) generally been confined to niche applications such as acoustics. Electromagnetic actuation may, however, lose its dominance, as several new actuator materials may compete directly with electromagnetics in both performance and cost for a wide range of applications. [1–6]

Actuator material performance is typically measured by a number of basic parameters including strain, actuation stress, energy density (mechanical output energy per stroke per unit volume or mass of material), response time, and theoretical efficiency (the efficiency obtained with ideal electronics). Electromagnetic actuation, while not the best in any of these measures of performance, is reasonably good in all such measures. This suggests that good overall performance is key to the wide applicability of an actuator material.

Perhaps as a result of the rapid advancement of polymer materials in the latter part of the 20th century, many of the new actuator materials have been polymers, specifically electroactive polymers. One new polymer actuator approach with good

---

*Much of this work was performed under the management of the Micromachine Center as the Industrial Science and Technology Frontier Program, Research and Development of Micromachine Technology of MITI (Japan), supported by the New Energy and Industrial Technology Development Organization.

†Dr. R. Pelrine, Mr. R. Kornbluh
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025 (USA)

Mr. Guggi Kofod
Risø National Laboratory, Fys 124
Roskilde 4000 (Denmark)

overall performance is dielectric elastomers (DEs),[1, 7] which consist of a polymer material sandwiched between two compliant electrodes. The electrodes can be made of a variety of compliant conductive materials such as colloidal carbon in a polymer binder. When a voltage difference is applied between the electrodes, the electrostatic forces resulting from the free charges squeeze and stretch the polymer. This well-known phenomenon, *Maxwell stress*, occurs with all insulators subject to an electric field from deposited electrodes.[8] However, in the past Maxwell stress has generally been regarded as a "nuisance" effect in polymers—too weak to provide good actuation by itself. With the development of soft polymer thin films with high dielectric breakdown strengths, this view is changing, and several materials with exceptional overall performance have been identified.

The actuator performance of dielectric elastomers can be quite high, particularly with respect to strain and energy density: acrylic elastomers have demonstrated actuated strains of over 200%, stresses of up to 7 MPa, and estimated energy densities of over 3 J/g.[1] One silicone, NuSil's CF19-2186, has demonstrated stresses of 3.0 MPa, 63% strain, response times of less than 1 ms, and theoretical efficiencies of 80–90%.[6]

2. Theoretical Description

Figure 1 illustrates the principle of operation of dielectric elastomers. As described above, the electrostatic forces due to the electrodes' voltage difference squeeze and stretch the film. The squeezing and stretching modes are coupled in an elastomer,[9] with the effective compressive stress, p, given by

$$p = \varepsilon \varepsilon_o E^2 = \varepsilon \varepsilon_o (V/z)^2 \quad [1]$$

where ε is the relative dielectric constant, ε_o is the permittivity of free space (8.85×10^{-12} F/m), E is the applied electric field, V is the applied voltage, and z is the film thickness. Strain is more difficult to estimate because it depends on a variety of parameters such as modulus and boundary conditions. For low strains (< 20%), the thickness strain, s_z, is given by $s_z = -p/Y$ for a material with constant modulus Y and free boundary conditions.

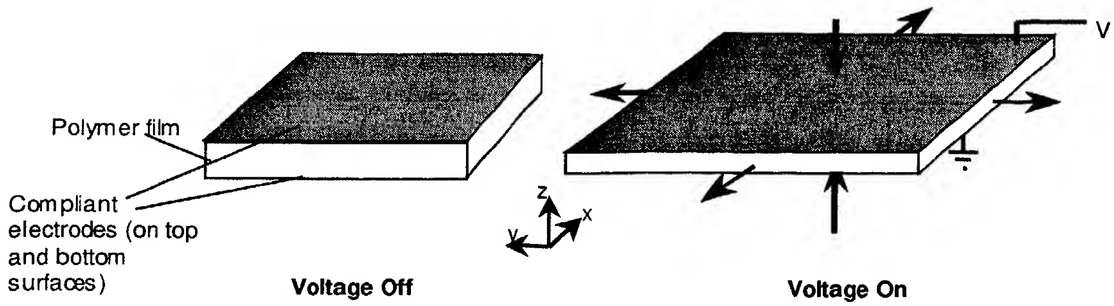

Fig. 1. Principle of operation of dielectric elastomer actuation.

Dielectric elastomers are closely related to electrostrictive polymers such as irradiated P(VDF-TrFE) and polyurethanes.[3,5] Generally speaking, most researchers use the term "electrostrictive polymers" to imply the actuation principally involves mechanisms other than Maxwell stress. It should be noted, however, that all electrostrictive polymers exhibit a component of Maxwell stress, and in many cases contribute as much as 10–50% of the total response.[10]

3. Experimental Methods

Typically, dielectric elastomers are fabricated by conventional polymer fabrication techniques such as spin coating and casting. Electrodes can be deposited via spraying, screen printing, or photolithography.[11]

Methods to test the performance of dielectric elastomers have been investigated and are an ongoing area of research. The large strains of the elastomer films, their flexible nature, and the possibility of edge arcing make measurement challenging. One method of testing performance is to stretch the film on a frame and pattern an electrode circle or line on a small portion of the stretched film, as illustrated in Figure 2. The active portion expands when voltage is applied and the strain is easy to measure optically. This "stretched film" method supports the film and eliminates boundary arcing, although it introduces boundary constraints. The stretched film technique also allows one to test various prestrains, which have been shown to dramatically increase the performance of some dielectric elastomers.[1]

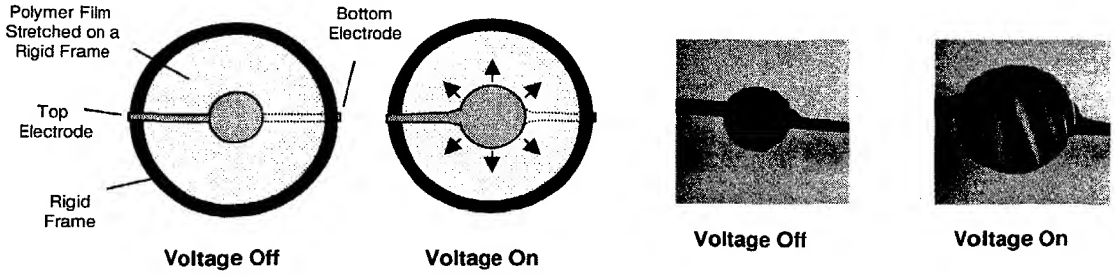

Fig. 2. Circular strain test and photo of acrylic dielectric elastomer.

The boundary constraints in the stretched film test can be modeled using finite element models with nonlinear material properties.[11,12] The finite element modeling gives good results at smaller strains, but even nonlinear finite element modeling may be unsatisfactory at larger strains, particularly if creep or viscoelastic effects are present. One way to address this issue is to measure changes in boundary forces rather than strains, as illustrated in Figure 3. The drawback of this method is that it does not give strain results; its advantage is that it can be applied to virtually any material. Equation 1 can be used with the force measurements and the parameter $b = \varepsilon\,\varepsilon_o / z^2$ to predict the stress as $p = b\,V^2$. Figure 3 shows preliminary data obtained from an acrylic elastomer (3M's VHB 4910), which fits a V^2 dependence exceptionally well. The data indicates that b is about 17% higher than the originally estimated value, b_{est}, which is not surprising since small errors in measuring ε and z can cause significantly larger errors in b. While the results do not rule out the use of an electrostrictive mechanism aside from the Maxwell stress, they suggest that under the test conditions its contribution to the total response is small.

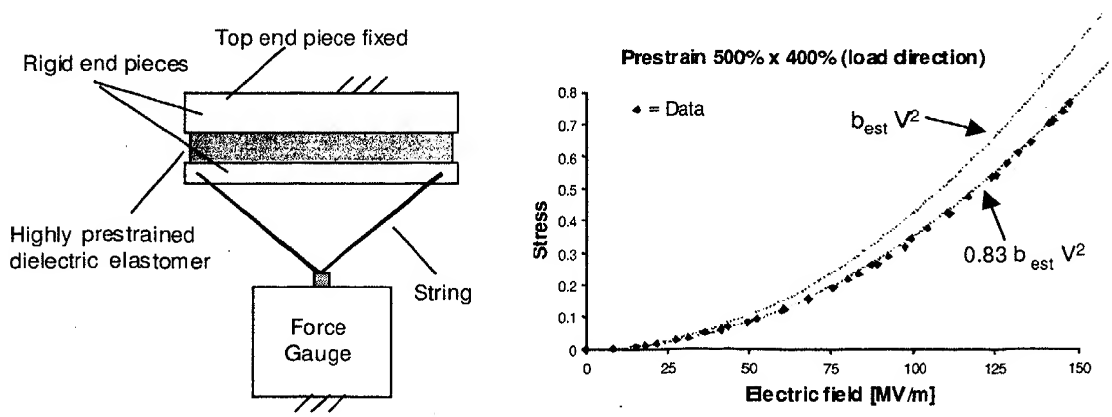

Fig. 3. Force test setup and example of experimental results from VHB 4910 acrylic and carbon grease elastomers.

4. Summary and Discussion

Dielectric elastomers are a new class of actuator materials that have exhibited excellent performance. From a materials viewpoint, the challenge is to identify the key parameters at a molecular level that contribute to good performance, and to use this understanding to synthesize new polymers with higher performance or other desirable properties such as environmental tolerance. The fabrication of the polymer-electrode structure is also an area of interest, particularly as the technology is scaled up for larger applications.

The description presented here considers only the fundamental performance of the material. Applications require functioning actuators as opposed to actuator materials. Typical applications include speakers, robot actuators, pumps, motors, linear actuators, and many others. A wide variety of dielectric elastomer actuators such as bimorphs, unimorphs, diaphragms, rolls, and planar linear actuators have been demonstrated.[7, 11] Most of these actuator designs use adaptations of approaches previously developed for other materials such as piezoelectrics. However, some novel actuator designs have been developed that specifically exploit the performance characteristics of DE materials and yield good results.[13] Thus, beyond research in the material and fabrication areas, much remains to be done in developing actuator designs that can optimally exploit the actuator properties of DE materials.

References

1. R. Pelrine, R. Kornbluh, Q. Pei, J. Joseph, *Science* **2000**, 287, 5454.
2. S. Park, T. Shrout, *J. Appl. Phys.* **1997**, 82.
3. Q. Zhang, V. Bharti, X. Zhao, *Science* **1998**, 280.
4. R. H. Baughman, C. Cui, A. Zakhidov, Z. Iqbal, J. Barisci, G. Spinks, G. Wallace, A. Mazzoldi, D. DeRossi, A. Rinzler, O. Jaschinski, S. Roth, M. Kertesz, *Science* **1999**, 284.
5. M. Zhenyi, J. I. Scheinbeim, J. W. Lee, B. A. Newman, *J. Polymer Sciences, Part B—Polymer Physics* **1994**, 32.
6. Y. Bar-Cohen, S. Leary, M. Shahinpoor, J. Harrison, J. Smith, *Smart Structures and Materials 1999: Electroactive Polymer Actuators and Devices, Proc. SPIE* **1999**, 3669.
7. R. Kornbluh, R. Pelrine, Q. Pei, S. Oh, J. Joseph, to appear in *Smart Structures and Materials 2000: Electroactive Polymer Actuators and Devices, Proc. SPIE* **2000**.
8. R. Anderson, *Phys. Rev. B* **1986**, 33, 2.
9. R. Pelrine, R. Kornbluh, J. Joseph, in *Sensor and Actuators A: Physical 64* **1998**.
10. Q. Zhang, J. Su, C. Kim, *J. Appl. Phys.* **1997**, 81, 6.

11. R. Kornbluh, R. Pelrine, J. Joseph, R. Heydt, Q. Pei, S. Chiba, *Smart Structures and Materials 1999: Electroactive Polymer Actuators and Devices, Proc. SPIE* **1999**, 3669.

12. L. Treloar, *J. Polymer Science Part C: Polymer Symposia* **1974**, 48.

13. R. Pelrine, R. Kornbluh, Q. Pei, J. Joseph, S. Chiba, in *Proc. Fifth Intl. Micromachine Symp.* **1999**.